Strength of Mineral Absorption Features in the Transmitted Component of Near-Infrared Reflected Light: First Results From RELAB

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Bidirectional reflectance measurements are the only type of reflectance data available to the remote observer. For compositional interpretations, data are desired not only for identification of possible mineral components but also for modal abundance. The latter requires detailed information about the strength of absorption features. Using a new laboratory facility, the RELAB, laboratory data in the near infrared are presented that document effects of particle size, mineral mixtures, and viewing geometry for selected materials with well-developed absorption bands. The commonly observed increase in reflectance with decrease in particle size is also observed for absorption bands as well as a related decrease in absorption strength. For small particles in parts of the spectrum of maximum reflectance, however, a minor decrease in reflectance with a decrease in particle size is sometimes observed. Small particles dominate the observed characteristics of particulate surfaces, which contain a range of particle sizes. The mean optical path length (transmission through particles) of reflected radiation measured for a variety of particle sizes has an apparent upper limit of about 2 mm for particles <250 μm. The typical number of particles involved in the optical path is less than 50.

INTRODUCTION

Spectral reflectance measurements of planetary surfaces in the visible and near-infrared wavelengths are a form of remote sensing data that provide primary information about the composition of surface material. The compositional information is inherent in well-defined mineral absorption features that are controlled by the composition and structure of the mineral [e.g., Burns, 1970]. The usefulness of the remotely sensed reflectance data is directly linked to a thorough understanding of the characteristic absorption features of specific minerals and rocks as well as the manner in which mineral characteristics combine when present as a naturally occurring mixture.

The substantial documentation of systematic visible and near-infrared reflectance properties of minerals [Adams, 1974, 1975; Hunt and Salisbury, 1970, 1976] has allowed an estimation of the composition of solar system objects that can be observed within the current limits of earth-based telescopes (see McCord and Cruikshank [1981] for a summary). Significant advances have also been made in the application of remote sensing reflectance data to understanding problems in terrestrial geology [Goetz and Rowan, 1981]. Recent developments in instrumentation for both earth-based telescopes as well as proposed future spacecraft allow measurements to be made with far better spectral resolution, spectral range, and precision than was available in the early 1970's. This new generation of observational data requires more sophisticated and systematic laboratory data on known materials. In particular, the effects of physical and chemical alteration, multicomponent mixtures, physical properties of soils, and viewing geometry of observations must be better understood. Useful theoretical models need to be utilized that expand the data base to include more of these important variables in applied reflectance spectroscopy.

Reflection of light from a particulate surface involves a number of physical processes, some of which are only partially understood (see, for example, texts such as those of Wendlandt [1968] and Kortum [1969]). First of all, simple reflection and transmission of radiation at a boundary between two media of different optical properties are generally described by Fresnel's equation and are dependent on the angle of incidence of incoming radiation and the index of refraction of the media as variables. Although often ignored, this first surface specular reflection (sometimes called single scattering) can be significant for particulate material, and for dark surfaces the reflected radiation is strongly polarized at large phase angles [e.g., Dollfus, 1961] as predicted by Fresnel's equations. Second, absorption characteristics of the transmitted component in an absorbing medium are described by the exponential Bouguer-Lambert law which relates resulting intensity to the absorption coefficient of the medium and path length. Almost all mineral absorption bands in a reflectance spectrum arise from absorption only of the transmitted component of radiation. Theoretical models for reflectance must include scattering functions. Scattering relationships between particles and at the boundary between the particulate material and the external medium or vacuum are complex, but are generally described from variations on radiative transfer theory some of which include absorption parameters [e.g., Hapke, 1981].

Reflectance of a given material can be measured (1) as a function of wavelength, (2) as a function of viewing geometry (angles of incidence, reflection, phase), and (3) as a function of polarization. Each of these three types of measurements emphasizes different aspects of the way light interacts with particulate materials. Although all of them are required to fully describe reflectance, they are rarely utilized together to constrain the interrelated transmitted, scattered, and specular components of reflection.

A variety of useful new reflectance data for specific applications are now being produced [e.g., Singer, 1981; Clark, 1981; Gradie et al., 1980]. There is a growing need for supporting laboratory information concerning the basic principles of reflection. In recognition of this need, a reflectance experiment laboratory (the RELAB) was designed and built by Lockheed Engineering and Management Services Company and is currently located at the Johnson Space Center, Houston. The RELAB instrument, used in this study, is described below prior to data presentation. The detection of absorption
features and the measured spectral energy (wavelength or frequency) at which they occur allow interpretations about the existence of mineral species on the surface: the measured strength of absorption features is linked in part to the relative proportions of minerals on the surface. Some of the initial basic reflectance experiments under way using the RELAB are described here and involve examination of parameters that affect the strength and nature of absorption features. A brief section on the use of analogue studies is also included to maintain at least one direct link with remote sensing applications.

**RELAB: INSTRUMENT DESCRIPTION**

The purpose of the RELAB is to allow the primary optical properties of surface reflection (reflectance, albedo, polarization) to be measured with high precision (~1%) and high spectral resolution (>1 nm) under geometric conditions comparable to those for earth-based or spacecraft reflectance measurements.

The RELAB can be described as a "directional reflectance spectrometer/polarimeter" or a "swinging arm spectrogoniometer." A sketch of the overall system is presented in Figure 1 with the major individual components identified. The optics are controlled by front-surface mirrors. Unpolarized monochromatic light is directed onto the uncovered horizontal sample at a chosen angle of illumination. The reflectance of the sample and reference standard (pressed halon) are measured in turn from a rotating sample platform for each spectral increment. The sampling resolution, spectral range, and phase angle can be independently chosen. A list of specifications is presented in Table 1.

The spectrometer is controlled by an LSI-1103 minicomputer with interactive software using a VT55 graphics terminal. The computer coordinates the electronics and the mechanical steps of the monochromater. The data are stored in memory and displayed on the graphics terminal as they are obtained. Each data run can involve up to 500 sampling steps. When a run is complete, the data are stored on floppy disk along with all identifying information.

The reference standard for all measurements is pressed halon. The standard is measured for each wavelength increment of the sample measurements. Raw data are stored for the sample, the standard, and the background. The ratio of the sample to the standard (both with background subtracted) is also stored in the data file and is the primary information displayed in the graphics mode. Amplifier gain of the detector and lamp voltage are monitored by the computer and are adjusted for maximum efficiency.

The reflectance properties of halon have been accurately measured by the National Bureau of Standards (1975 National Bureau of Standards test 232.04/213908). Halon is exceptionally white over the range 0.250 to 2.50 μm with a reflectance greater than 96%. Halon is an inert fluorocarbon that does not readily absorb water. The goniometric properties of halon reflectance measured in the RELAB are shown in Figure 2. The incident beam (~8 mm maximum) is always smaller than the sample (~10-mm dish); the field of view of the detector (~5-mm maximum) is always within the incident beam. These results indicate that our halon standard is nearly Lambertian.

### Table 1. RELAB Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength range (reflectance spectra)</td>
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</tr>
<tr>
<td>Wavelength range (polarization spectra)</td>
<td>4-2.0 μm (projected)</td>
</tr>
<tr>
<td>Cooled detectors</td>
<td>visible—photomultiplier infrared—inSb</td>
</tr>
<tr>
<td>Slit</td>
<td>fixed (1 mm)</td>
</tr>
<tr>
<td>Gratings</td>
<td>590 lines/mm for 0.45-1.7 μm</td>
</tr>
<tr>
<td></td>
<td>295 lines/mm for 1.7-2.7 μm</td>
</tr>
<tr>
<td>Angle of incidence range</td>
<td>0°-60°</td>
</tr>
<tr>
<td>Angle of reflection range</td>
<td>0°-60°</td>
</tr>
<tr>
<td>Phase angle range</td>
<td>12°-120°</td>
</tr>
<tr>
<td>Sampling resolution</td>
<td>≥1 nm</td>
</tr>
<tr>
<td>Precision of data</td>
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</tr>
</tbody>
</table>

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**Fig. 1.** Reflectance experiment laboratory (RELAB). Unpolarized monochromatic radiation is incident on a horizontal uncovered sample. All optics and components of the incident beam are rotated as a unit as the angle of incidence (i) is varied. All components of the reflected beam (e) are on a separate plane of rotation.
Fig. 2. Reflectance properties of pressed halon (open circles) measured in the RELAB as a function of phase angle (p). For comparison the halon data are scaled to the value of a cosine function (solid circles) at a 10° angle of incidence (i).

The RELAB has been designed to have multiple users and is accessible with a remote terminal and telephone line modem to set up measurement parameters and examine and transfer completed data measurements. A VADIAC modem, which can be used with standard telephone lines, is used for this purpose (up to 1200 baud). A handbook for remote users has been prepared and is available on request. Planned upgraded capabilities for the RELAB facility include implementation of polarizing optics allowing spectral polarimetric measurements, extension of the spectral range of measurements, and implementation of an environment chamber.

**Particle Size Separates**

A RELAB study undertaken by King et al. examines the effects that particle size has on an absorption feature in a three-component mineral mixture. The first results of that study have been presented [King et al., 1981] and are summarized here. It has been demonstrated that the strength of a well-defined absorption feature depends not only on the amount of absorbing mineral present but also on the overall opacity of the surface material [Nash and Conel, 1974; Pieters, 1974]. Earlier studies [e.g., Adams and Filice, 1967] had also demonstrated strong effects that the particle size has on general reflectance characteristics. One of the objectives of remote spectral reflectance measurements is to be able to estimate the modal mineralogy of surface material. The measured strength of an absorption feature is key information in this endeavor, but the mixing systematics of the variables that affect absorption strength have not been fully understood. In this study, specific minerals were chosen for preparation of controlled mixtures of different compositions and different particle sizes. Absorption strength and peak reflectance (albedo) were examined in relation to these variables.

Three minerals were selected for the experiments described here: plagioclase feldspar (Lake County, Oregon, labradorite), enstatite (enstatite component of websterite, Webster, North Carolina), and ilmenite (Baie Saint Paul, Quebec). The labradorite was chosen for its relatively high albedo and broad absorption feature centered near 1.25 μm. This is used as a brightening component in the mineral mixing experiments. The enstatite is an orthopyroxene and was selected for its characteristic Fe²⁺ absorption feature centered near 0.91 μm.

Fig. 3. Reflectance spectra of labradorite, enstatite, and ilmenite for four particle size separates: (1) < 30 μm, (2) 30–45 μm, (3) 45–108 μm, and (4) 150–250 μm. Geometry of all measurements is i = e = 15° with a phase angle of 30°.
Fig. 4. Spectra of two-component mineral mixtures involving enstatite and ilmenite. Mixture ratios are shown in the upper right panel. The reflectance spectra on the left are unsealed bidirectional reflectance relative to a halon standard (i = e = 15°). The spectra on the right are the same data scaled to unity at 1.18 μm. A separate sequence for each of four particle size separates is shown. As the opaque component increases, the overall albedo decreases (left), and the absorption strength (right) decreases in a nonlinear manner.

The ilmenite has a low albedo and a relatively featureless spectrum and is used as a darkening component.

The mineral having a well-defined absorption band in all the data presented here is the enstatite (EN99, websterite). Since this mineral is birefringent, a single representative absorption coefficient at any wavelength cannot be measured directly from transmission spectra of individual crystals. The observed absorption feature at 0.91 μm arises from the combined absorption of the transmitted component for randomly oriented crystals. The effective absorption coefficient is, of course, the same in all data presented here, and the relative strength of the observed absorption is only a function of the controlled variables (particle size, modal mixture, geometry).

All mineral samples were examined with the petrographic microscope to ensure that there was no visible contamination. The samples were hand-ground and sieved in freon to maintain purity and assure that smaller particles would not adhere to the larger. The particle size ranges used in the experiment were 150–250 μm, 45–108 μm, 30–45 μm, and <30 μm. Within each sieve fraction no further analyses of size and
shape were made. The spectra for each of these simple size ranges for the three minerals are shown in Figure 3. These and other spectra for this part of the experiment were obtained at a 30° phase angle ($i = e = 15°$).

To examine the effects a dark component has on absorption strength, two component mixtures of the ilmenite and enstatite were prepared for each grain size range. The prepared ratios of enstatite/ilmenite in these mixtures are 93/7, 90/10, and 85/15 in weight percent. Reflectance spectra for these mixtures are shown in Figures 4 and 5.

The general systematics from Figure 4 are evident: (1) As the proportion of opaque component increases, the albedo decreases, and the absorption strength decreases in a nonlinear manner. (2) The effect is different for various particle sizes with the smallest particle size showing the greatest reduction in absorption strength with increasing opaque content. For the larger particles there is only a small difference between mixtures with 7% ilmenite and those with 10%. This lack of distinction is not understood but is likely to be coupled with the specular properties of the opaque materials. Note that in...
Figure 3 the larger opaque particles are less dark and show less spectral contrast than the smaller particles.

The general effects of particle size on absorption strength are evident in Figure 5: as the particle size decreases, the absorption band depth and spectral contrast decrease. Since samples of different particle sizes for each compositional group have the same spectral absorption coefficients, the decrease in absorption strength must be due to a decrease in the mean optical path length of the transmitted component through the bulk material. Simple multiple scattering effects [e.g., Morris et al., 1982] cannot account for these observations, however, since reflectance does not vary regularly with particle size at all wavelengths. For example, the 93/7 enstatite/ilmenite mixture reflectance data show an increase in
reflectance with decreasing particle size at 0.90 μm but a different pattern at 1.20 μm (further discussed below in the section on the transmitted component of reflection).

**PARTICLE SIZE DISTRIBUTIONS**

Naturally occurring particulate surfaces may have differences in average particle size, but in most cases are not composed of simple particle size separates such as the data of Figures 4 and 5. For example, with lunar soils there is a strong inverse correlation between grain size and standard deviation [McKay et al., 1974]. “Mature” lunar soils have a relatively well constrained bell-shaped frequency distribution of grain sizes with a mean between 30 and 60 μm. Younger soils are skewed toward larger particles and are sometimes bimodal. Because of the complex nature of most particulate surfaces and soils, it would be presumptuous to claim to produce a valid match of observed properties with simple laboratory samples. Since surface material may have a range of particle sizes, controlled distribution samples were prepared from the separates for further study of reflection systematics and comparison with the simpler case.

Three 100% enstatite and two 90/10 enstatite/ilmenite “soils” were prepared from the separates shown in Figure 5. Spectra for these samples with a distribution of particle sizes are shown in Figure 6. The weight percent proportions of each size fraction included in these soils are (from smallest size fraction to largest) S 35/40/15/10; E 25/25/25/25; L 10/15/40/35.

Some of the same systematics observed for the size separates are also seen for these samples with a distribution of particle sizes. Stronger absorption features are observed for soils with a large portion of large particles (L). However, the range of measurable parameters such as absorption strength and maximum reflectance is severely reduced for the samples that contain a distribution of particle sizes. This information is summarized graphically in Figure 7. Values for absorption strength are percent absorption at 0.91 μm relative to an estimated continuum (a straight line tangent to the reflectance spectrum across an absorption band). The small particles (<45 μm) dramatically reduce the strength of an absorption feature even when present in relatively small amounts (25% in the L soils).

**VIEWING GEOMETRY**

For any given sample (or surface), viewing geometry also affects the strength of the measured parameters [e.g., Adams and Filice, 1967; Pieters, 1974; Gradie et al., 1980]. For relatively bright samples the effects due to geometry are often smaller than those due to variations in physical properties and modal mineralogy, but are nevertheless significant. The effects of phase angle on the spectrum of a 100% enstatite are presented in Figure 8 for comparison with the effects of other
variables discussed previously. In all cases the incident angle $i$ was set equal to the emission angle $e$. To compensate for the photometric properties of the halon standard, the cosine scaled spectra can be considered equivalent to bidirectional reflectance for equal area measurements under differing viewing geometry. For this enstatite sample, overall reflectance decreases with increasing phase angle, but the only significant variation in absorption band strength occurs for large phase angles. Since this enstatite sample is a single mineral with strong spectral features, the transmitted component of reflected light plays a dominant role in the measured spectral characteristics. Viewing geometry may have a more dramatic effect on absorption strength for weaker absorption bands when the transmitted component is reduced in the total reflected radiation (e.g., opaque rich surfaces).

**Analogue and Compositional Trends**

Reflectance measurements of samples in the laboratory are utilized from two approaches as the basis for compositional interpretations. In the first approach, data obtained remotely for some unknown surface are compared to similar measurements in the laboratory of possible analogue material. If the properties match, the unknown surface is assumed to have compositional properties similar to those of the analogue. The inverse is also true if the properties do not match. For the second approach, each possible variable associated with a measurement is examined separately in the laboratory. Interpretations for remotely obtained data discuss a range of properties that could account for observed characteristics. In application, both approaches are often combined.

Figure 9 (left panel) contains two laboratory and two telescopic reflectance spectra of lunar and lunar analogue material. Spectrum $a$ is a laboratory reflectance spectrum of Apollo 16 soil 62331, a feldspathic soil containing abundant glass-welded aggregates called agglutinates [e.g., Adams and McCord, 1973]. The two telescopic spectra are from small areas in Mare Serenitatis: spectrum $b$ is for a fresh crater, and spectrum $c$ is for a nearby mature mare surface. A straight line continuum can be estimated and removed for these three spectra [e.g., McCord et al., 1981], and their residual absorption features compared (Figure 9, right panel).

In all three lunar spectra the characteristic absorption features of pyroxene near 1 and 2 $\mu$m can be identified [Adams, 1974]. Furthermore, the detailed compositional trends of pyroxenes studied by Adams [1974] in the laboratory together with the clear differences in energy (wavelength) of the observed lunar absorption bands indicate that the composition of the pyroxene for the Apollo 16 sample is a low calcium orthopyroxene, while the pyroxenes for the unsampled mare areas are more calcium- and iron-rich clinopyroxenes. The differences between the two telescopic Serenitatis spectra are due to the alteration processes that occur on the lunar surface. The mature soil (spectrum $c$, right panel) is darker than the fresh crater (spectrum $b$) and has a weaker absorption band...
due to the accumulation of dark agglutinates as the surface is exposed to the solar wind and micrometeorites (see summary in the work by Pieters [1978]). The nature of agglutinates is partially understood from returned lunar soils. The reflectance trends that occur with the gradual accumulation of these dark components have been studied in the laboratory [Adams and McCord, 1973; Nash and Conel, 1973] and are comparable to those described in the previous section concerning an increase in the opaque component (ilmenite). Returned lunar soils also show a decrease in particle size as a soil matures [McKay et al., 1974]. In this example it is clear that the compositional trends related to the accumulation of agglutinates are the dominant effect on absorption strength and particle size variation creates only a minor effect.

The highland Apollo 16 sample (d) and the mare soil at MS2 (c) are both mature lunar soils, and their characteristics can be compared directly. The differences in overall reflectance (albedo) and the strength of the pyroxene absorption bands are due to primary compositional differences between these two terrain types. The maria are less feldspathic and more mafic than the highlands (which accounts for their lower albedo). The maria also contain a higher abundance of pyroxene (which is primarily responsible for the major differences in absorption strength).

Early measurements of the physical properties of some lunar analogue material, common and exotic cheese, indicated sound velocities comparable to returned lunar rocks [Schreiber and Anderson, 1970]. The spectral characteristics of comparable samples, however, provide contrary evidence using direct analogue comparison with lunar materials. Both blue (green) cheese and Jack cheese (spectrum d in the left panel of Figure 9) exhibit the same spectral characteristics which conclusively show that this simple analogue material can be removed from reasonable consideration.

TRANSMITTED COMPONENT OF REFLECTION

Since spectral absorption features of minerals arise from the transmitted component of surface reflection, it would be worthwhile to reexamine the relation between transmission and reflectance spectroscopy in the near infrared. An isotropic didymium glass (Schott BG-36) with numerous absorption bands was chosen for this purpose. A transmission spectrum was obtained for a 1-mm-thick piece of this glass using a spectrometer system at the University of Massachusetts (courtesy of R. L. Huguenin). This spectrum is plotted in Figure 10 as percent transmission for ease of comparison with the reflectance data. To account for reflections from the front and rear surfaces when calculating internal absorption coefficients, these values are divided by 0.88 (derived from the refractive index supplied by Schott). Under the same procedures as described previously this BG-36 glass was ground and sieved to four particle size separates. Reflectance spectra for these size separates are shown in Figure 11 (i = e = 15°).

All samples in Figure 11 have the same spectral absorption coefficient and refractive index and are measured under the same geometric arrangement. The only variable in these controlled samples is particle size. A similar situation exists for the data of Figure 5. Even a qualitative examination of the data in Figure 11 indicates that particle size must affect at least two properties of how light interacts with particulate materials. The most obvious is the total transmitted path length of light through particles making up the bulk material: the smaller the particle size, the smaller the mean optical path length (MOPL) or total penetration distance through particles before the light is scattered out of the material. The reduced path length due to increased scattering results in less absorbance and for any regular scattering law, such as the Kubik-Munk theory [Kortum, 1969], also results in an increase in overall reflectance. This is clearly the dominant effect of particle size and is evident in all the major absorption bands.

There are also less well defined effects in this glass that appear to result in a loss of total reflected radiation as the spectral contrast is being reduced. At wavelengths where the absorption coefficient $\kappa$ is very low (e.g., at 1.15 $\mu$m where $\kappa < 0.01$ $\mu$m$^{-1}$) a decrease in peak reflectance is observed as particle size is decreased. The BG glass samples were also measured using a different geometric configuration ($i = 0^\circ$, $e = 30^\circ$), and the same decrease of reflectance was observed for the small particle sizes. The relative proportion of the specular first surface component of reflection (as yet unmeasured) may account for some of this secondary effect. The known nonisotropic nature of particulate surfaces (deviation from Lambertian surface reflection [e.g., Hapke and Welles, 1981]) may also contribute to these observations. Both possibilities merit further investigation.

A quantitative analysis of the transmission and reflectance...
particulate surface the maximum transmitted path length in the visible and near-infrared wavelengths is thus of the order of 2 mm. The glass data, however, are ideal; as opaques are included in the surface material, the path length is further reduced (see Figure 4), and the MOPL would be expected to be less than 2 mm. The measured variation of MOPL with particle size documents the observed qualitative trends: as particle size decreases, the effective path length of the transmitted component decreases. The data in Table 2 and Figure 12 also demonstrate the dramatic, almost logarithmic effect that absorption strength has on the path length: as the absorption coefficient increases, the MOPL decreases.

The number of particles that effectively provide the total transmitted path length in this interaction can be estimated by dividing the MOPL by the average path length through each particle, estimated as \( \frac{1}{2} \) the particle diameter. Since the four size separates each include a range of values within the sieve limits, the mean of the sieve sizes was used as a mean particle diameter. The <30-\( \mu \)m data are not well bounded by this procedure. Estimates of the typical number of particles involved are presented in Table 2. These data should be very useful in designing reflectance models of mineral mixtures.

There appears to be an upper limit of 45 to 48 for the number of particles encountered in visible and near-infrared reflectance of typical silicate particulate surfaces.

Recall that in the above discussion these estimates of MOPL use measurements of the strength of absorption bands relative to a continuum for both the transmission data, used to calculate the absorption coefficient \( \kappa \), and the reflectance data for different particle sizes. This procedure was chosen because it can be performed independently of what is occurring to the overall nature of the continuum. To perform similar calculations using measured values for the absorption coefficient of the continuum would not be proper and would require all the properties of scattering to be accurately defined.

### Summary of Highlights

A variety of specific details about how light interacts with a particulate surface are evident in the data presented here. Emphasis has been on parameters that affect the strength of mineral absorption bands in the near infrared, a key measurement in remote sensing of surface composition.

Particle size of surface material has a strong effect on the path length possible for the transmitted component of total reflection. In a normal soil mixture, however, the smaller particles dominate the interaction with light even though they make up a minor component of the soil. Although most materials show an increase in reflectance with decrease in particle size, the opposite (a decrease in reflectance) is often observed for small particles at wavelengths of maximum reflectance.

### Table 2. Mean Optical Path Length of Reflected Radiation for Different Particle Sizes of BG-36

<table>
<thead>
<tr>
<th>Particle Size, ( \mu )m</th>
<th>Assumed Mean Size, ( \mu )m</th>
<th>MOPL, mm</th>
<th>Number of Particles</th>
<th>MOPL, mm</th>
<th>Number of Particles</th>
<th>MOPL, mm</th>
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<td>&lt;30</td>
<td>15</td>
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<td>46</td>
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<td>0.11</td>
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<tr>
<td>30–45</td>
<td>38</td>
<td>0.91</td>
<td>48</td>
<td>0.33</td>
<td>17</td>
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<td>45–108</td>
<td>75</td>
<td>1.67</td>
<td>45</td>
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<tr>
<td>108–250</td>
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<td>0.66</td>
<td>7.5</td>
<td>0.31</td>
<td>3.5</td>
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</table>

MOPL is mean optical path length.
Limits can be placed on the extent of light interaction with particulate materials. The longest mean optical path length of the transmitted component for near-infrared absorption bands is of the order of 2 mm for particles <250 μm and requires large particles and relatively transparent media. The apparent maximum number of particles involved in the path length is less than 50, and the larger number requires relatively transparent media. Particulate surfaces or complex soils are more likely to have a mean optical path length of less than 1 mm and involve perhaps 20 or fewer particle interactions.

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